Kai Yang[a], *Ming Li Jiao, **Yi-Song Chen, **Jun Li, **Wei-Yuan Zhang

School of Fashion and Art
***Department of Materials and Chemistry, Zhongyuan University of Technology,**
Zhengzhou, Henan, China

****College of Fashion, Donghua University,**
Shanghai, China
[a]No. 41 West Zhengzhou Road,
Zhengzhou, 450007, China
E-mail:kaikai_422@yahoo.com.cn

Analysis and Prediction of the Dynamic Heat-Moisture Comfort Property of Fabric

Abstract
A series of experiments and analyses were performed to study the dynamic heat and moisture transferring procedure as well as evaluate the heat-moisture comfort property of fabric in wearing conditions that produce continued sweat. By measuring five static indexes of ten different fabrics, which involved static heat-moisture transmission through fabric, as well as two dynamic comprehensive indexes obtained from the dynamic curves using a self-made microclimate measuring apparatus, the relation between the static indexes and dynamic comprehensive indexes was established.In addition, an evaluation and prediction system for the dynamic heat-moisture comfort property of the textile was formulated by means of the grey system theory. For two different environmental conditions: the most comfortable ones, and an extremely uncomfortable condition for humans, four different prediction models were built, and high predictive precision was obtained.

Key words: *dynamic heat-moisture comfort, temperature and relative humidity, microclimate measuring apparatus, grey system theory.*

Introduction

Heat and moisture handling properties of textiles are regarded as a major factor in the comfort performance of clothing in normal use. For many years lots of researches have concentrated on the heat-moisture transfer of clothing in steady states [1]. The actual dissipation of heat and moisture is not always in a steady state, especially under the influence of human physiology, psychology and environment. Nowadays, many researchers are gradually realising that the there are many differences in dynamic heat-moisture transfer in a steady state and, as a result, focus on the study of the dynamic comfort of clothing [2 - 5]. However, because of the complexity of dynamic heat-moisture transfer and the limitation of experimental apparatuss, researchers cannot perform dynamic tests [6]; they can only test when a certain steady state is reached. Using this method, many instantaneous changes cannot be known, which affects the real observation of dynamic heat-moisture transfer and further impacts objective judgment on the comfort property of clothing. There is still a need to study the heat and moisture comfort properties of textiles under transient conditions to better understand textiles and clothes [7].

This study examines the real time changes in the temperature and relative humidity of a textile using a self-made microclimate measuring instrument under transient conditions and further analyses and evaluates the dynamic heat-moisture comfort property of fabric. This study also established the relativity of the textile's static parameters, as well as dynamic comprehensive indexes to predict the dynamic comfort using static parameters.

Experimental

Apparatus and materials

The textile-microclimate measuring apparatus used in this study is shown in ***Figure 1***, which is a system for simulating the skin-microclimate-fabric system during sweating. The apparatus was of a cylindrical shape so that the heat and moisture could be transferred by one dimension, perpendicular to the fabric. The whole apparatus was wrapped in polyurethane plastic as a heat insulation layer, except the fabric surface, which was exposed to the environment. The fabric was held taut in an embroidery hoop and mounted over simulated sweating skin, which consisted of a chamois heated to a skin temperature of about 33 °C. A relative humidity of about 100% was maintained by a PID temperature controlling apparatus. Four distances between the fabric and simulated skin were selected by changing different grooves: 5, 10, 15 and 20 mm.

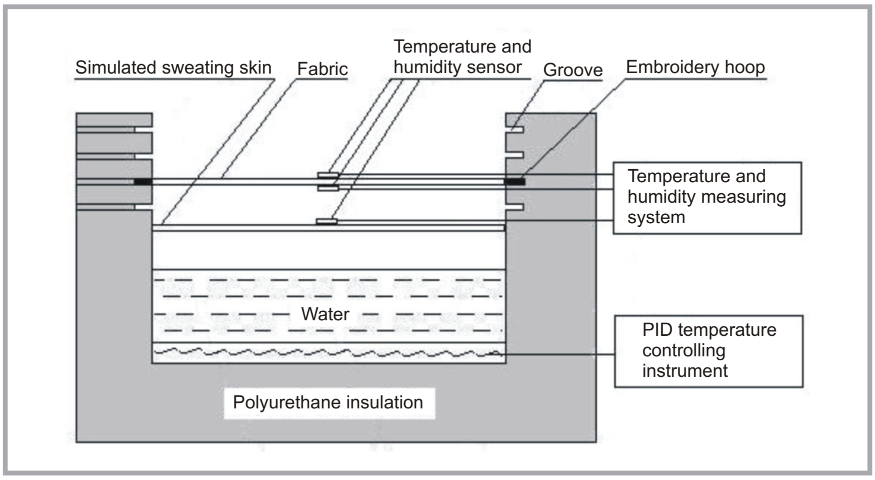


Figure 1. *Textile-microclimate measuring apparatus.*

The equipment was used to measure the surface temperature and relative humidity of the textile. Two Pt100 temperature and humidity sensors were employed to detect the surface temperature and relative humidity on the inner and outer surfaces of the fabric. A temperature and humidity measuring system, programmed by LabVIEW [8, 9] - energetic and functional virtual apparatus software, was used in an industrial measuring and controlling field to detect the voltage changes of the sensors and convert them into temperature and relative humidity values. After filtering valid temperature and humidity data, they were then stored in chart and electronic form for transfer and analysis afterwards.

We selected ten different kinds of fabric as samples. Their descriptive characteristics are given in ***Table 1***. They have similar styles and are all used in summer as well as spring and ,therefore, have a certain comparability in their heat-moisture comfort properties.

Experimental procedures

There were two parts of the experiment: a static experiment using standard apparatus, the other a dynamic experiments using self-made microclimate apparatus. All test fabrics were conditioned in a test atmosphere for 24 hours prior to testing. In order to describe the static heat-moisture transfer property of the textile, five static experiments (thickness, weight per square meter, air permeability, moisture regain, and vertical wicking height) were performed. The thermal conductivity of the textile was also an important parameter which has a high correlation with thickness and weight per square meter. The thickness and weight per square meter were the basic parameters of the fabric, as they were easier to measure than the thermal conductivity; hence, a thermal conductivity experiment was not performed. Results of the static experiments are given in ***Table 1***.

Table 1. *Descriptive characteristics and static indexes of test fabrics.*

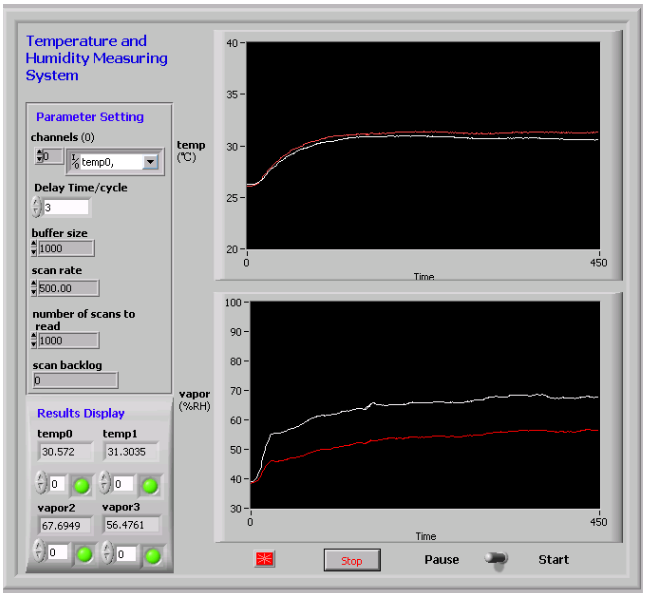
No.	Component	Blending ratio	Thickness, mm	Weight, g/m2	Air permeability, mm/s	Moisture regain, %	Vertical wicking height, cm
1	Nylon+Cotton	65%/35%	0.38	129.24	249.04	4.84	10.08
2	Cotton	100%	0.60	130.59	264.06	6.20	5.00
3	Acrylon	100%	0.65	188.29	418.65	13.30	14.50
4	Viscose+Linen	55%/45%	0.50	217.18	114.89	9.22	8.00
5	Cotton	100%	0.49	189.89	55.29	5.52	6.20
6	Richcel+Spandex	92%/8%	0.81	242.11	412.11	10.31	1.67
7	Modal+Cotton	50%/50%	0.86	236.76	174.83	7.81	4.50
8	Polypropylene	100%	1.05	286.44	375.10	0.06	1.30
9	Silk	100%	0.16	69.69	605.72	7.60	3.38
10	Bamboo+Cotton	65%/35%	0.41	268.82	51.62	15.97	10.50

The dynamic experiments were especially designed to evaluate the dynamic comfort property of the textile, which were completed under two different environmental conditions in a climate chamber. The first parameters were selected of: (25 ± 1) °C, and (50 ± 2)% RH, which is regarded as a comfortable environment for human beings, andwhereas the second of (33 ± 1) °C, and (80 ± 2)% RH, which is extremely uncomfortable for humans. Before testing, the simulated sweating skin was heated to maintain a skin temperature of (33 ± 0.5) °C and a relative humidity of (97 ± 2)%. After fixing the temperature and humidity sensors to the fabric, which was held taut in an embroidery hoop, the temperature and humidity measuring system was turned on (the front panel of this system is presented in ***Figure 2***), and the embroidery hoop was immediately inserted into one side of the microclimate apparatus . In this experiment the air gap between the simulated sweating skin and the inner surface of the test fabric was set 10 mm, and after inserting the embroidery hoop with/into the test fabric over the skin, the relative humidity of the simulated sweating skin reached (100 ± 2)%. The computer recorded and displayed the temperature and humidity changes in the inner and outer surfaces of the test fabric every 3 s. This data recording rate (3 s) was chosen with reference to many other experiments. If the rate would longer than 3 s, the system could not catch real time changes in the fabric's temperature and relative humidity, because after inserting the fabric into the apparatus, the fabric's temperature and relative humidity increased rapidly. If the rate would be shorter than 3 s, the fabric's temperature and relative humidity data would be too rapidly changed, which made post data processing difficult.

Results and discussion

Evaluation of dynamic heat-moisture comfort

After the dynamic experiments reported above, we got ten temperatures and humidity curves of the test fabrics varying with time in two different environmental conditions. Typical temperature and relative humidity variation curves are given in ***Figure 3***. T_1 is the time of inserting the embroidery hoop with fabric into the microclimate apparatus, and T_2 is the time of reaching dynamic heat or moisture balance on the inner surface of the fabric. H_1 is initial temperature or relative humidity of the fabric, and H_2 is the av-



channels (0): 0, temp0,

Delay Time/cycle: 3

buffer size: 1000

scan rate: 500.00

number of scans to read: 1000

scan backlog: 0

temp0: 30.572 — 0

temp1: 31.3035 — 0

vapor2: 67.6949 — 0

vapor3: 56.4761 — 0

Figure 2. *Front panel of the temperature and humidity measuring system.*

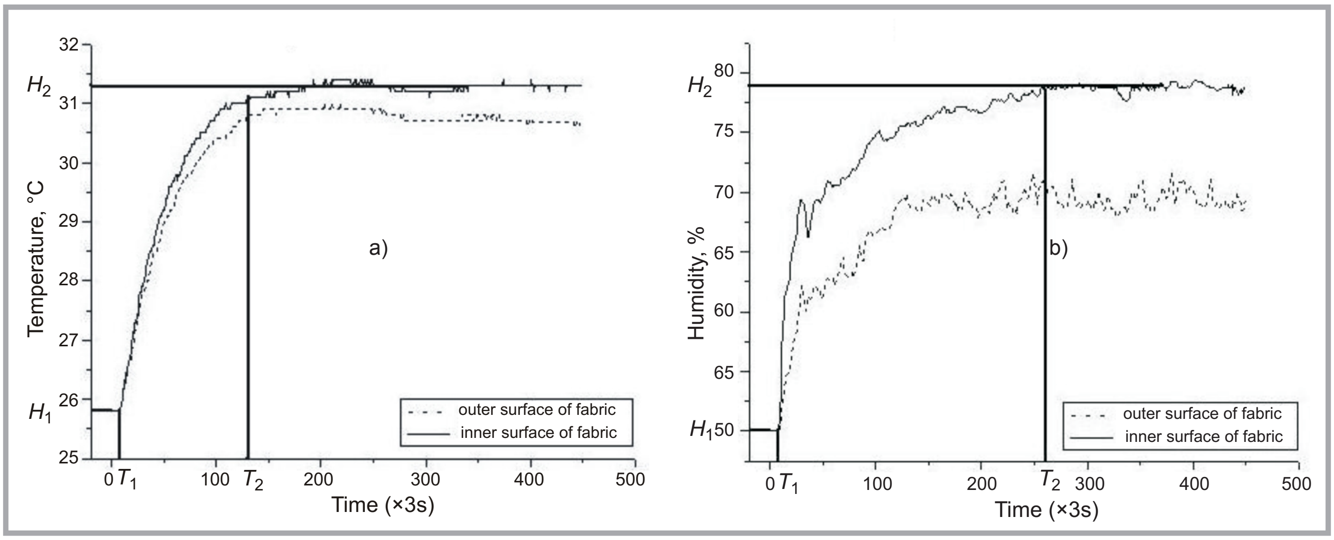


Figure 3. *Typical temperature (a) and relative humidity (b) variation curves recorded by the measuring system presented in **Figure 2**.*

erage maximum of temperature or relative humidity of the fabric when dynamic heat or moisture balance on the inner surface of the fabric is reached. ***Figure 3*** shows that there are distinct styles and variation regularities at different stages. During the initial balance, the temperature and humidity in the inner and outer surfaces of the fabric are the same with respect to the environment. After inserting the fabric into the apparatus, with the evaporation of sweat from the simulated skin, the temperature and humidity in the microclimate increase rapidly. At the same time, the temperature and humidity in the fabric's inner surface and the gradient between the two sides of the fabric also increase rapidly. After a while the ascending velocity of the temperature and humidity tends to level out. When the evaporation rate from the simulated skin is equivalent to the diffusion rate from the fabric to the environment, a new balance is achieved, and the temperature and humidity retain a static state.

From the dynamic relative humidity curves in ***Figure 3***, we can get such dynamic characteristic values as follows:

1. Difference of initial ascending slope between the inner and outer surfaces of the fabric (S_{mois} in %/min): It is the difference of the ascending slope of the fitting straight line in the first 30 s of testing which illustrates the fabric's moisture sorption and transfer abilities upon immediate exposure to a high humidity microclimate. The more rapid the humidity build-up in the fabric surface, the stronger the stimulus for possible sensations of discomfort is.
2. The time of reaching the dynamic balance in the inner surface of the fabric (T_{mois} in min = T_2 - T_1): This value is calculated by stepwise derivation to the dynamic curves after smoothness handling. Fabrics that have good moisture transfer and dissipatiion properties will reach dynamic balance more quickly, and humans will feel more comfortable.
3. The ascending average maximum of humidity in the inner surface of the fabric when dynamic balance is reached (Δmax_{mois} in % = H_2 - H_1): This value illustrates the fabric's moisture transmission and dissipation abilities. The more rapidly the moisture dissipates through the fabric, the lower the humidity reacheds during the balance time, and the lower the intensity of discomfort perceived by the wearer at that time. Is this sentence clear.

From the dynamic temperature curves in ***Figure 3***, we can also get the following three dynamic characteristic values: S_{heat} in °C/min, T_{heat} in min, $\Delta\max_{heat}$ in °C, which have the same meaning as S_{mois}, T_{mois}, $\Delta\max_{mois}$, respectively.

In order to comprehensively evaluate the dynamic comfort property of the fabric, we introduce two comprehensive indexes of dynamic heat and moisture comfort - Dy_{heat} and Dy_{mois}.

$$Dy_{heat} = \frac{C_1}{S_{heat} \times T_{heat} \times \Delta\max_{heat}}$$

$$Dy_{mois} = \frac{C_2}{S_{mois} \times T_{mois} \times \Delta\max_{mois}}$$

Where C_1 and C_2 are two dimensionless constants. To make the value of Dy_{heat} and Dy_{mois} not too big or not too small, and almost in the range of 1 to 50, we set C_1 = 100 and C_2. =10,000.

From the above formula we can see that the unit of Dy_{heat} is (°C)$^{-2}$, and the unit of Dy_{mois} is (%)$^{-2}$. Therefore, the bigger Dy_{heat} and Dy_{mois} are, the more comfortable heat and moisture properties the fabric will have. To differentiate the dynamic heat and moisture comfort properties of the fabric under comfortable and uncomfortable conditions, we define that $Dy_{heat\text{–}com}$ means the heat comfort property of the fabric under comfortable conditions, $Dy_{heat\text{–}uncom}$ means the heat comfort property of the fabric under uncomfortable conditions, $Dy_{mois\text{–}com}$ means the moisture comfort property of the fabric under comfortable conditions, and $Dy_{mois\text{–}uncom}$ means the moisture comfort property of the fabric under uncomfortable conditions.1)

A bar diagram of the comprehensive dynamic indexes of the fabrics tested by us is given in ***Figure 4*** (see page 54). From ***Figures 4*** (***a***) and (***b***) we can see that under comfortable conditions the dynamic heat comfort properties of the fabrics are similar, while under uncomfortable conditions, they are very different: test fabric property No. 2 is the best, whereas test fabric property No. 8 is the worst. From ***Figures 4*** (***c***) and (***d***) we can see that under comfortable conditions dynamic moisture comfort property No. 9 is the best, while under uncomfortable conditions, almost all the moisture comfort properties of the fabrics are worse, except test fabrics No. 3 and No. 9.

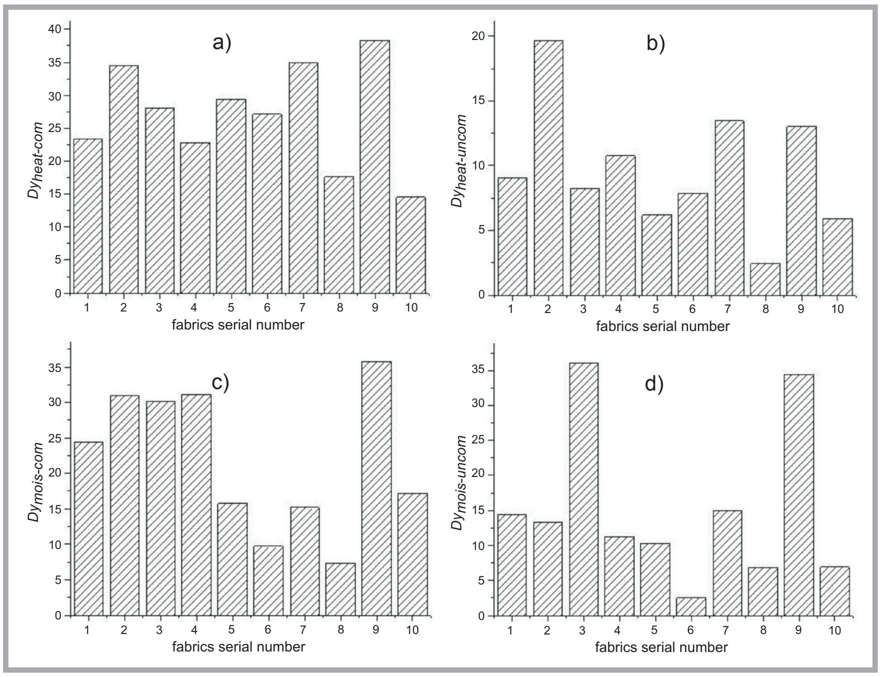


***Figure 4.** Bar diagram of the dynamic comprehensive indexes of the test fabrics; a) dynamic heat comfort property under comfortably condytion, b) dynamic heat comfort property under uncomfortably condytion, c) dynamic moisture comfort property under comfortably condytion, d) dynamic moisture comfort property under uncomfortably condytion.*

Prediction of dynamic heat-moisture comfort

Dynamic experiments can evaluate the comfort property of textiles more effectively, but they are more time and energy consuming complex than static experiments. Moreover the complicated equipment and advanced recording apparatus needed are not always available. Hence, the grey system theory is introduced to establish models that can describe the relationship between static measuring indexes and dynamic comprehensive indexes. Firstly, a grey interrelationship analysis was performed to establish the static indexes that had a high degree of association with the dynamic comprehensive indexes. The degrees of grey incidence of dynamic comprehensive indexes to static indexes are given in Table 2.

Table 2 illustrates that $Dy_{heat\text{–}com}$ and $Dy_{heat\text{–}uncom}$ have a high degree of grey incidence with thickness, weight, air permeability of fabrics, whereas $Dy_{mois\text{–}com}$ and $Dy_{mois\text{–}uncom}$ have a high degree of grey incidence with air permeability, moisture regain, and the vertical wicking height of the fabrics under two different environmental conditions. In order to find the relation between them, we use the grey mathematical modelling method to establish models to predict the dynamic comprehensive indexes using static theparameters. The procedures are as follows, taking the prediction of $Dy_{heat\text{–}com}$ as an example:

1. Find the original data series.
   $X_j = \{x_{j(1)}, x_{j(2)}, \ldots x_{j(k)}, \ldots, x_{j(n)}\}$,
   ($j = 0, 1, 2, 3$; $k = 1, 2, \ldots, n$; $n = 10$).
   where X_0 is $Dy_{heat\text{–}com}$, X_1 is the thickness, X_2 is the weight per square meter, and X_3 is the air permeability.
2. Perform preliminary treatment on the original data using the followingthis formula: $x_j'_{(k)} = x_{j(k)}/x_{j(1)}$.

And then perform an accumulated generating operation to every data series using this formula:

$$x_j^{(1)}(k) = \sum_{i=1}^{k} x_j'(i)$$

Next, get a new data series:

$X_j^{(1)} = \{x_j^{(1)}{}_{(1)}, x_j^{(1)}{}_{(2)}, \ldots\ldots x_j^{(1)}{}_{(n)}\}$,
($j = 0, 1, 2, 3$; $n = 10$).

3. Suppose, we accept the following differential equation of the first order.

$$dX_0^{(1)}/dt + aX_0^{(1)} = b_1X_1^{(1)} + + b_2X_2^{(1)} + b_3X_3^{(1)}$$

where $a\hat{} = (a, b_1, b_2, b_3)^T = = (B^TB)^{-1}B^TY_N$,

$Z_0^{(1)}{}_{(k)} = [x_0^{(1)}{}_{(k)} + x_0^{(1)}{}_{(k-1)}]/2$,

$$B = \begin{bmatrix} -Z_0^{(1)}(2) & x_2^{(1)}(2) & x_3^{(1)}(2) & x_4^{(1)}(2) \\ -Z_0^{(1)}(3) & x_2^{(1)}(3) & x_3^{(1)}(3) & x_4^{(1)}(3) \\ \hdashline -Z_0^{(1)}(0) & x_2^{(1)}(0) & x_3^{(1)}(0) & x_4^{(1)}(0) \end{bmatrix}$$

$Y_N = (x_0'_{(2)}, x_0'_{(3)} \ldots\ldots x_0'_{(10)})^T$.

After calculation, $a\hat{} = (-0.7188, 0.4099, -1.0116, 0.1908)^T$, the first order differential equation is

$$dX_0^{(1)}/dt - 0.7188X_0^{(1)} = 0.4099X_1^{(1)} + - 1.0116X_2^{(1)} + 0.1908X_3^{(1)}$$

4. Write the response function according to the first order differential equation:

$$X_{0(k)}\hat{} = \sum_{i=1}^{3} (b_i \times x_i^{(1)}(k)) - a \times Z_0^{(1)}(k)$$

5. Calculate the relative residual error / using this formula:

$$e = \left| \frac{x_{0(k)}\hat{} - x_{0(k)}}{x_{0(k)}} \right|$$

***Table 2.** Degree of grey incidence; **Notes**: Table 2 only indicates the degree of grey incidence, and it can not indicate the polarity of grey incidence, i.e. positive correlation or negative correlation.*

Factor	Thickness	Weight	Air permeability	Moisture regain	Vertical wicking height
$Dy_{heat\text{–}com}$	0.663	0.646	0.653	0.564	0.584
$Dy_{heat\text{–}uncom}$	0.725	0.683	0.658	0.611	0.549
$Dy_{mois\text{–}com}$	0.636	0.613	0.693	0.659	0.793
$Dy_{mois\text{–}uncom}$	0.579	0.579	0.752	0.647	0.766

***Table 3.** Prediction models of dynamic comprehensive indexes; **Notes:** $X_0^{(1)}$ is $Dy_{heat\text{–}com}$ or $Dy_{heat\text{–}unom}$; $Y_0^{(1)}$ is $Dy_{mois\text{–}com}$ or $Dy_{mois\text{–}unom}$; $X_1^{(1)}$ is thickness; $X_2^{(1)}$ is the weight per square meter; $X_3^{(1)}$ is the air permeability; $X_4^{(1)}$ is the moisture regain; $X_5^{(1)}$ is the vertical wicking height.*

Factor	First order differential equation
$Dy_{heat\text{–}com}$	$dX_0^{(1)}/dt - 0.7188X_0^{(1)} = 0.4099X_1^{(1)} - 1.0116X_2^{(1)} + 0.1908X_3^{(1)}$
$Dy_{heat\text{–}uncom}$	$dX_0^{(1)}/dt - 2.379X_0^{(1)} = - 0.8052X_1^{(1)} - 2.2697X_2^{(1)} + 0.3999X_3^{(1)}$
$Dy_{mois\text{–}com}$	$dY_0^{(1)}/dt + 0.823Y_0^{(1)} = 0.5011X_3^{(1)} + 0.393X_4^{(1)} + 1.3525X_5^{(1)}$
$Dy_{mois\text{–}uncom}$	$dY_0^{(1)}/dt + 0.8797Y_0^{(1)} = 0.9375X_3^{(1)} - 0.5964X_4^{(1)} + 1.4101X_5^{(1)}$

Using the method reported above, we get the prediction models of dynamic comprehensive indexes, which are given in ***Table 3***. According to the relative residual error test, the predictive precision of each model is above 90%. From these prediction models we can see that under comfortable conditions fabrics with lower weight per square meter, higher thickness and air permeability will be more heat-comfortable, while fabrics with higher air permeability, moisture regain and vertical wicking height will be more moisture-comfortable. Under uncomfortable conditions fabrics with lower thickness and weight per square meter, higher air permeability will be more heat-comfortable, while fabrics with lower moisture regain, higher air permeability and vertical wicking height will be more moisture-comfortable. The prediction models in ***Table 3*** also show that fabric indexes have different effects on dynamic comfort under different conditions, therefore fabric indexes and environmental conditions should be seriously considered during the study of the dynamic comfort properties of fabric, which in fact requires further investigation.

Conclusions

This study investigated the dynamic heat-moisture comfort property of textiles based on static and dynamic experiments. By testing the temperature and humidity changes of the inner and outer surfaces of ten different fabrics during dynamic heat-moisture transfer under two different environmental conditions, we get temperature and humidity variation curves and their characteristic values for every fabric, as well as introduce two comprehensive indexes to evaluate the dynamic heat and moisture comfort property of the textile. By means of the grey system theory, prediction models based on the first order differential equation are established to predict the dynamic heat-moisture comfort property of the textile under two different environmental conditions, which indicate that under comfortable conditions, fabrics with lower weight per square meter, higher thickness and air permeability will be more heat-comfortable, while fabrics with higher air permeability, moisture regain and vertical wicking height will be more moisture-comfortable. Under uncomfortable conditions fabrics with lower thickness and weight per square meter as well as higher air permeability will be more heat-comfortable, while fabrics with lower moisture regain, higher air permeability and vertical wicking height will be more moisture-comfortable.

Editorial note

[1] The following sequences are statements of the Author Kai Yang as a reply to remarks of the reviewers.
Whether the range limits that determine the dynamic comfort property of the fabric are good or not is a matter opinion. When I wrote the article, I wanted to classify the fabrics into three levels according to their comfort property, which were good, medium and bad. AlthoughI was the first to introduce the Dy_{heat} and Dy_{mois} formula, I had no references to consult. Therefore, I set the range limits myself using related knowledge of the subjective evaluation of clothing. Moreover, I read some original articles where the authors introduced their new theory and evaluated methods; therefore, set my own range limits, which I admit were a little random.

References

1. *Ruckman J. E.; 'Water Vapor Transfer in Waterproof Breathable Fabrics, Part I: Under Steady-State Conditions', International Journal of Clothing Science and Technology, 1997, No 1, pp. 10-22.*
2. *Robin W. D.; 'Transient Comfort Phenomena Due to Sweating', Textile Research Journal, 2001, No 9, pp. 796-806.*
3. *Chen Y. S., Fan J., Zhang W.; 'Clothing Thermal Insulation During Sweating', Textile Research Journal, 2003, No 2, pp. 152-157.*
4. *Li Y., Zhu Q. Y.; 'Simultaneous Heat and Moisture Transfer with Moisture Sorption, Condensation, and Capillary Liquid Diffusion in Porous Textiles', Textile Research Journal, 2003, No 6, pp. 515-524.*
5. *Fohr J. P., Couton D., Terguier G.; 'Dynamic Heat and Moisture Transfer through Layered Fabrics', Textile Research Journal, 2002, No 1, pp. 1-12.*
6. *Holmer I., Elnas S.; 'Physiological Heat Transfer by Clothing', Ergonomics, 1981, No 1, pp. 63-74.*
7. *Kim J. O.; 'Dynamic Moisture Vapor Transfer through Textiles. Part III: Effect of Film Characteristic on Microclimate Moisture and Temperature Changes', Textile Research Journal, 1999, No 3, pp. 193-202.*
8. *Wayne Labs; 'National Instruments Updates LabVIEW with Pattern Matching, Adds Multiserver/Multiclient Connectivity to Lookout', Instrument & Control Systems, 1999, No 10, pp. 74.*
9. *Chen Y. S., Zhao T., Turner B.; 'A New Computerized Data Acquisition and Analysis System for KES-FB Instrument', Textile Research Journal, 2001, No 9, pp. 767-770.*

Received 06.11.2006 Reviewed 28.12.2007